Optimum resistance analysis and experimental verification of tristable energy harvesting from human motion

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Abstract: The complex dynamic behavior of nonlinear energy harvesters make it difficult to identify the optimum mechanical and electrical parameters for maximum output power, when compared to traditional linear energy harvesting devices. In addition, the random and variable characteristics of low-frequency human motion signals provide additional challenges for enhancing the energy harvesting performance, such as the traditional frequency domain analysis method being inappropriate for optimum resistance selection. This paper provides a detailed numerical and experimental investigation of the influence of load resistance on the efficiency of nonlinear tristable energy harvesting from human lower-limb motion. Numerical simulations under human motion excitations indicate that the optimum load resistance of a tristable energy harvester can be attained to maximize the power output. In addition, simulations of linear, bistable, and tristable harvesters under harmonic excitations verify the effectiveness of the frequency domain method in the absence of a change in the dynamic behavior of the harvester. Experimental measurements of the harvested power

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under different speeds of motion and load resistances are in good agreement to the numerical analysis for the tristable energy harvester. The results demonstrate the effectiveness of the proposed load resistance optimization method for tristable energy harvesting from human motion.

Keyword: Piezoelectric; Tristable energy harvesting; Human motion; Optimum load resistance.

1. Introduction

Vibration energy harvesting techniques have received considerable attention in recent decades due to its promising ability to convert ambient vibration energy to useful electrical energy for the supply of electricity for low-power consumption devices such as sensors and wireless transceivers[1-3]. In particular, the use of energy harvesting for body-worn or body-attached applications has been the subject of a significant amount of research interest as it has the potential to power modern low-power sensor systems and increase the mobility and independence of users[4-6]. Currently, there are a variety of transduction mechanisms based on piezoelectric[7-9], electromagnetic[10, 11], or thermoelectric[12] effects for converting human kinetic energy and motion to usable electric energy. Among them, piezoelectric vibration energy harvesting has been considered to be a promising method to harness natural body movements to power wearable electrical devices such as healthcare watches, pacemakers, and mobile phones, due to its high energy density and easily miniaturized fabrication[13]. In order to overcome the inability of linear energy harvesters to perform well under stochastic excitations, such as ambient vibrations and low-frequency human motion, the theoretical analysis and experimental validation of the frequency bandwidth and performance enhancement of harvesters as a result of introducing nonlinear phenomenon has received significant interest[14-16]. This includes a number of investigations on monostable[17-19], bistable[20-22] and tristable[23-27] configurations under harmonic and stochastic excitations. The results of these studies indicate that the introduction of nonlinearity can improve the energy harvesting performance, but the efficiency is greatly influenced by the shape of potential energy function of the harvesting system. Furthermore, extensive research had been carried out to determine the set of optimum mechanical and electrical parameters in order to maximize the output power of both linear and nonlinear energy harvesters [28-33]. Previous investigations on energy harvesters are almost all under harmonic and stochastic excitation[17-33]. However, real excitation signals generated by human motion exhibit a degree of randomness and variability[11], which will increase the difficulty to determine the optimal performance using electro-mechanical models and may result in the inability of the traditional analysis methods[28] used for harmonic and stochastic excitation to determine the optimum conditions. Therefore, an effective method should be developed to optimize the mechanical and electrical parameters for maximum energy generation under real human motion excitation.

A number of research publications have been devoted to determine the optimum resistance for maximizing the power output of vibration energy harvesters under different ambient excitations. Roundy and Wright[31] developed an analytical model of a linear piezoelectric energy harvester to estimate the delivered power and also discussed a detailed expression for the optimum load resistance under harmonic excitation. Zhao and Erturk[33] investigated the expected output power under Gaussian white excitation based on a proposed distributed-parameter model, and demonstrated the effectiveness of the analytical and numerical prediction methods under different base acceleration levels. Cammarano *et al.*[28] discussed the optimum load resistance for a linear energy harvester by applying a Fourier transform, and also introduced a two-parameter numerical optimization method which can be used to obtain the optimum load resistance of a nonlinear energy harvester with electromagnetic transduction for a fixed sinusoidal excitation. Although these analytical and experimental investigations of the optimum load resistance of linear and nonlinear bistable energy harvesting under the ideal harmonic and stochastic excitation have been undertaken, the investigation of the optimum resistance of a tristable energy harvester under real human motion has not been studied.

Therefore, this paper undertakes a detailed investigation into the relationship between power output and load resistance of a tristable energy harvester under real human motion excitations. Numerical simulation and experimental verification are conducted to obtain the optimum resistance of a tristable energy harvester under a variety of human motion speeds. Firstly, the theoretical analysis and simulation of optimum resistance for linear energy harvesters are introduced based on a Fourier transform. The numerical investigation of bistable, tristable and linear energy harvester under real human motion excitation as well as the fixed frequency harmonic excitation is presented to demonstrate that there is always a peak in the average power output for a range of load resistance when subjected to human motions or harmonic excitation. Finally, it is demonstrated that human motion experiments of tristable energy harvesting under different speeds of motion and load resistances exhibit a good agreement with numerical simulations.

The remainder of the paper is organized as follows: the electromechanical model of a tristable harvester with time-varying potential energy function is introduced in Section 2; the theoretical analysis and numerical simulations of the optimum load resistance are carried out in Section 3; Section 4 is an experimental verification under different human motion speeds; finally the conclusions are given in Section 5.

2. Description and electromechanical model

During the normal human motion process, the left and right legs strike the ground alternatively. There are two main acceleration-based excitation sources, namely the impact-based acceleration between the shoe and the ground as well as the acceleration caused by the swing motion of leg. In previous investigations into energy harvesting from human motion, there are a number of impact-based harvesters but only a limited number concerning swing motion. For example, Ylli *et al.*[11] presented a multi-coil topology harvester using the swing motion of the foot and tests under different speeds of motion revealed that the swing-type harvester can achieve an average output power up to 0.84 mW. Recently, Cao *et al.*[34] applied a bistable cantilever to harvesting energy from human motion and proposed a nonlinear model with time-varying potential energy function based on the swing motion of the human lower-limb.

In this paper, a nonlinear energy harvester applied to harvesting energy from human motion is the configuration illustrated by Cao *et al*.[34], shown in Fig. 1.(a). Monostable, bistable and tristable oscillators can be obtained by adjusting the nonlinear restoring force of the cantilever depending on the geometric parameters d, h, and θ. In this paper a tristable configuration with three stable equilibrium points (**1**, **3** and **5**) and two unstable ones (**2** and **4**) is investigated since its capability of harvesting energy from low frequency ambient vibration. When the tristable configuration is applied to harvesting energy from human lower-limb motion, the swing motion of lower-limb will drive the cantilever to swing a certain angle(shown in Fig. 1.(b)), which will result in a time-varying potential energy function due to the gravity of the cantilever. Thus the fundamental model can be given by the following equation[34]:

$$\begin{cases} m\ddot{x}(t)+c\dot{x}(t)+\dfrac{dU(x,\beta(t))}{dx}-\vartheta v(t)=-ma(t) \\ C_p\dot{v}(t)+v(t)/R+\vartheta\dot{x}(t)=0 \end{cases} \tag{1}$$

Where m, c, ϑ are the equivalent mass, the equivalent damping and the equivalent electromechanical coupling coefficient. C_p is the equivalent capacitance of the piezoelectric materials and R is the load resistance. $a(t)$, $x(t)$ and $v(t)$ are respectively the external excitation, tip displacement of the harvester and the voltage across the load resistance. $U(x,\beta(t))$ is the time-varying potential energy function described as the integral of nonlinear restoring force depending on the geometric parameters and the swing angle $\beta(t)$. It is found that the time-varying potential energy function is mainly attributed to the effect of gravity under different swing angles where the magnetic force similar to $\beta = 0$. Therefore, the restoring force of the nonlinear harvester can be approximated by:

$$F_r(x, \beta(t)) = F_h - mg\sin(\beta(t)) \tag{2}$$

where F_h is the restoring force for $\beta = 0$ and in this equation it is assumed that the clockwise angle is positive otherwise negative.

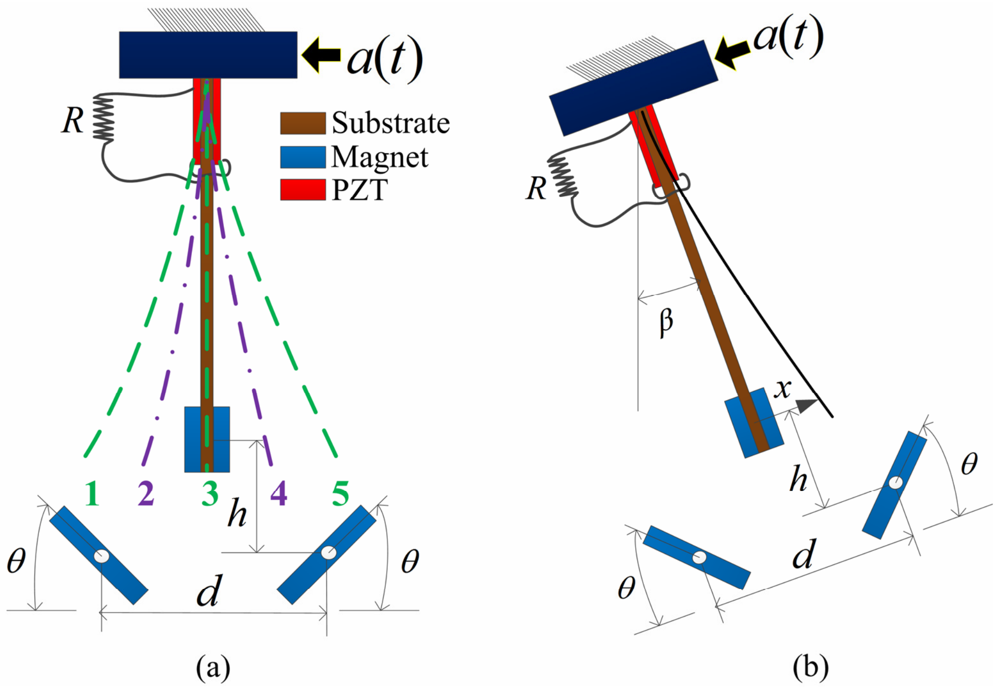


Fig. 1 (a) Schematic of the nonlinear energy harvester (1, 3, 5 are stable equilibrium points while 2, 4 are unstable points) and (b)system swing at a certain angle

3. Numerical analysis

3.1 Optimum resistance analysis of a linear energy harvester

For a conventional linear energy harvester, the frequency domain analysis method is initially used to determine the optimum load resistance in order to maximize the output power. The electromechanical model of linear energy harvester can be described by the following equation,

$$\begin{cases} m\ddot{x}(t) + c\dot{x}(t) + Kx - \vartheta v(t) = -m\ddot{y} \\ C_p \dot{v}(t) + v(t)/R + \vartheta \dot{x}(t) = 0 \end{cases} \tag{3}$$

where y is the displacement of base excitation and K is the linear stiffness. Applying a Fourier transform to equation (3) results in (4) and (5) respectively,

$$-m\Omega^2 X(\Omega) + cj\Omega X(\Omega) + KX(\Omega) - \vartheta V(\Omega) = m\Omega^2 Y(\Omega) \tag{4}$$

$$C_p j\Omega V(\Omega) + \frac{V(\Omega)}{R} + \vartheta j\Omega X(\Omega) = 0 \tag{5}$$

Finding the value of $V(\Omega)$ from equation (5) and substituting it into equation (4) we can obtain $X(\Omega)$ expressed by

$$X(\Omega) = \frac{m\Omega^2 Y(\Omega)}{\left(K - m\Omega^2\right) + \left(c + \dfrac{\vartheta^2}{C_p j\Omega + \dfrac{1}{R}} \right) j\Omega} \tag{6}$$

Hence, the average power dissipated in the electrical load over a cycle can be evaluated as

$$P = \frac{V^2}{2R} = \frac{m^2\vartheta^2\Omega^6 Y^2(\Omega)}{2R\left[\left(\dfrac{K - m\Omega^2}{R} - cC_p\Omega^2\right)^2 + \left(KC_p - mC_p\Omega^2 + \vartheta^2 + \dfrac{c}{R}\right)^2 \Omega^2\right]} \tag{7}$$

Under a fixed frequency excitation, the optimum load resistance can be determined by differentiating equation (7) with respect to R. The resulting optimum load resistance is expressed by

$$R_{opt} = \sqrt{\frac{\left(K - m\Omega^2\right)^2 + \Omega^2 c^2}{\Omega^2\left[\left(KC_p - m\Omega^2 C_p + \vartheta^2\right)^2 + c^2 C_p{}^2 \Omega^2\right]}} \tag{8}$$

Additionally, the piezoelectric layers can be viewed as a capacitance for the piezoelectric energy harvester, thus on that condition the equivalent resistance can be calculated by

$$R^{'} = 1/2\pi f C_p \tag{9}$$

Considering that the output power reaches a maximum value when the connected load resistance is equal to the equivalent internal impedance, the optimum load resistance can also be expressed by equation (9).

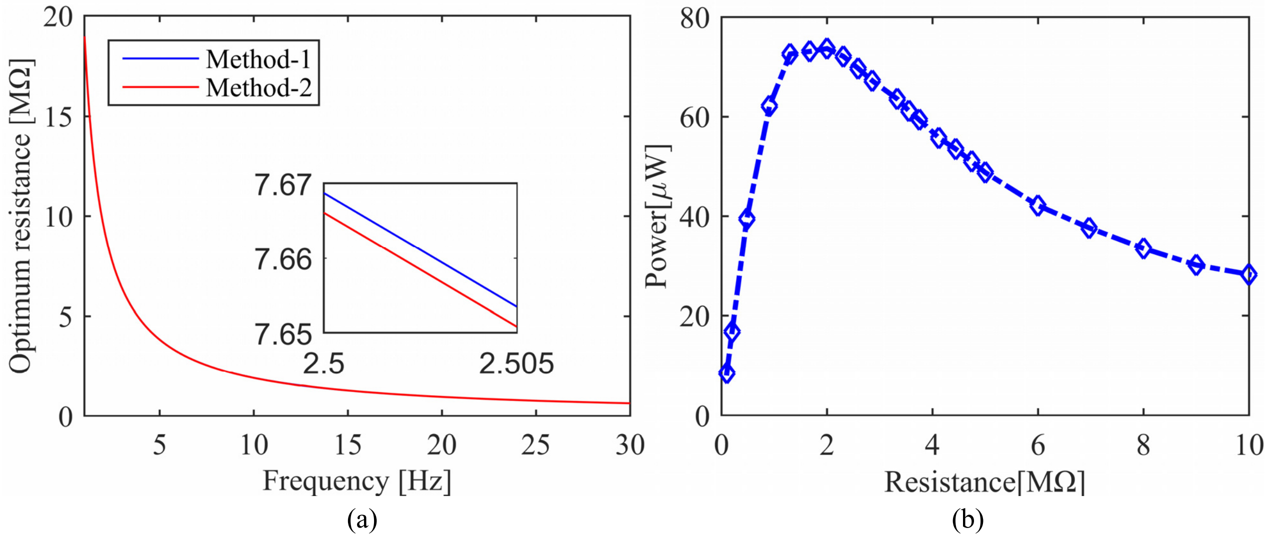


Fig. 2 (a) Relationship between the optimum load resistance and vibration frequency for a linear harvester; (b) relationship between output power and load resistance for linear energy harvester under harmonic excitation.

To verify the effectiveness of the proposed method for calculating the optimum load resistance, an experimental system was designed. PZT-51 was chosen as the piezoelectric material for its high energy density (d_{31}=190×10^{-12}C/N). The substrate layer of the harvester (Fig. 1) had dimensions of 95×10×0.27 mm^3, two PZT-51 piezoelectric layers connected in parallel had dimensions of 12×10×0.6 mm^3. Two endmost magnets had dimensions of 8×6×4 mm^3.The parameters in the electromechanical model were obtained by the method proposed by Zhou[27], namely K=23.569 Nm^{-1}, m=3.82×10^{-3} kg, c=5.89×10^{-3} Nsm^{-1}, C_p=8.3015×10^{-9} F, ϑ =−8.0627×10^{-6} NV^{-3}. These parameters were used to calculate the optimum load resistance under different frequency harmonic excitations based on equation (8) (Method-1) and (9) (Method-2), the numerical results are plotted in Fig. 2 (a). It can be seen that the optimum resistance decreased with an increase of frequency and the two methods have a very small discrepancy for calculating the optimum load resistance, therefore the equation (9) can be used to calculate the optimum resistance of linear harvesters for brevity. Experiments under harmonic excitation with an acceleration level of 5.5m/s^2 show that the experimental results are consistent with the theoretical methods. Fig. 2 (b) illustrates one set of experimental results under 12Hz and the optimum load resistance is approximately 2 MΩ, which has an acceptable difference with 1.59 MΩ calculated from the theoretical method.

3.2 Optimum resistance analysis of nonlinear energy harvesters

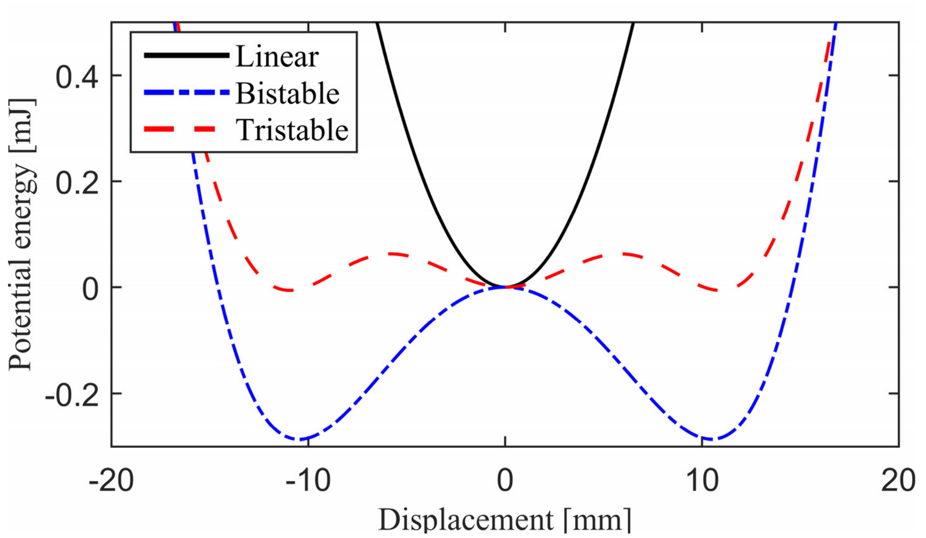


Fig. 3 Potential energy function of the linear, bistable and tristable energy harvesters

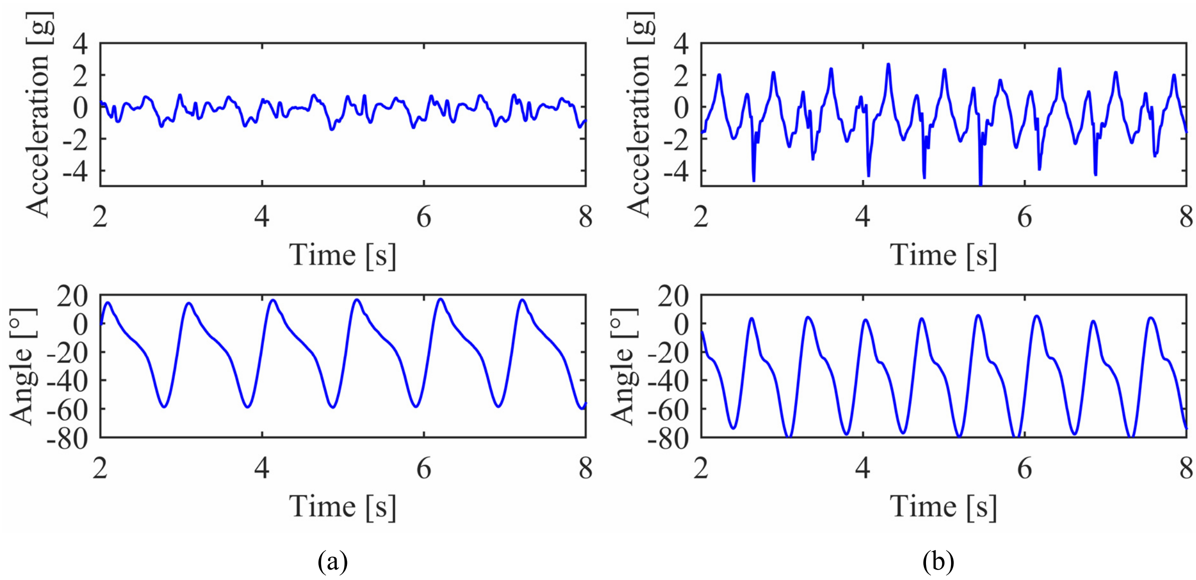
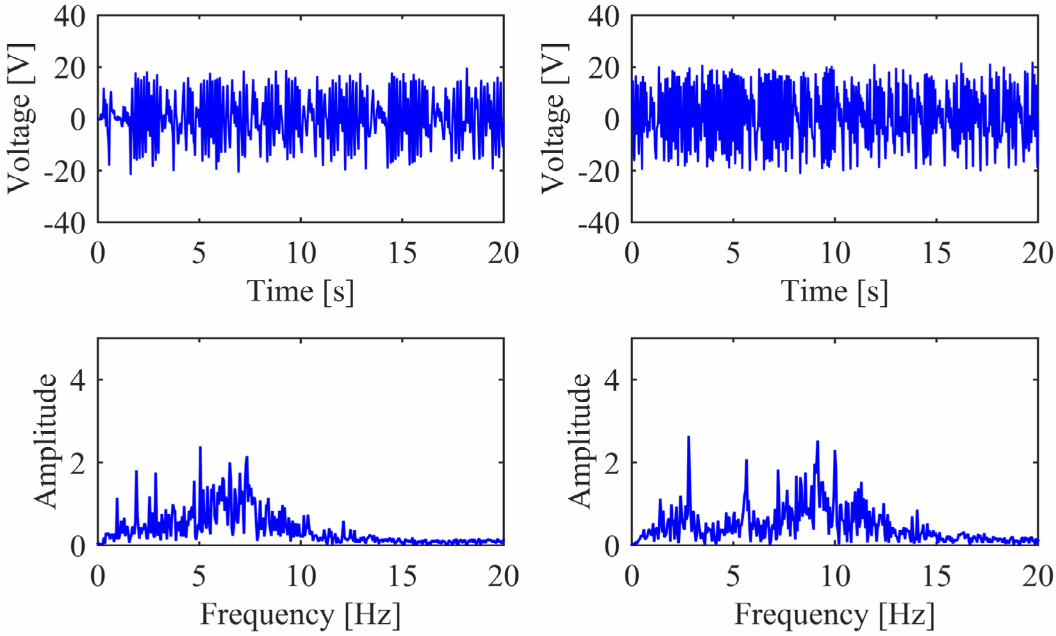


Fig. 4 Acceleration and swing angle data at speed of (a) 4 km/h and (b) 8 km/h

In this section, a tristable energy harvester with an appropriate potential well depth modulated through an experimental method is applied to analyze the optimum resistance of energy harvesting from human motion numerically. Real human motion signals obtained from experiments are used to excite the electromechanical model (1) and the potential energy function used for the tristable energy harvester is shown in Fig. 3, which also shows the potential energy functions of linear and bistable systems as they will be compared later. During the experimental process, human motion signals are measured at different speeds of 4~8 km/h on a treadmill, and in the next numerical simulation the acceleration and swing angle for speed of 4km/h and 8 km/h are considered as an input excitation. Fig. 4 shows the recorded acceleration and swing angle history at a speed of 4 km/h and 8 km/h. It can be seen that the measured acceleration enlarges with an increase of motion speed and there is a degree of quasi-periodicity and asymmetry. For a speed of 4 km/h, the swing angle ranges from -60° to 15°, while from -80° to 5° for speed of 8 km/h. It is also found that the increasing speed of motion enlarges the backward swing angle and reduces the forward swing angle.



(a) (b)

Fig. 5 Voltage response and the corresponding frequency spectrum under speed of (a) 4 km/h and (b) 8 km/h

The acceleration and swing angle data under the speed of 4 km/h and 8 km/h are used to excite the electromechanical model of the tristable energy harvester. The voltage response in the condition of open circuit connection and the corresponding frequency spectrum are illustrated in Fig. 5. It can be seen that under these speeds the tristable energy harvester can travel across the potential wells and generate a large output voltage (larger than 20V). Due to the larger acceleration as a result of increasing speed of motion, the cantilever undergoes inter-well oscillations more frequently at the speed of 8 km/h. Furthermore, because of the random and variable characteristics of low-frequency human motion signals as well as the nonlinear restoring force, the frequency spectrum of the voltage response in Fig. 5 exhibits multiple frequencies characteristics under different motion speeds, which will result in the traditional frequency-domain analysis method (mentioned in 3.1) being inappropriate to maximize the output power for linear energy harvester.

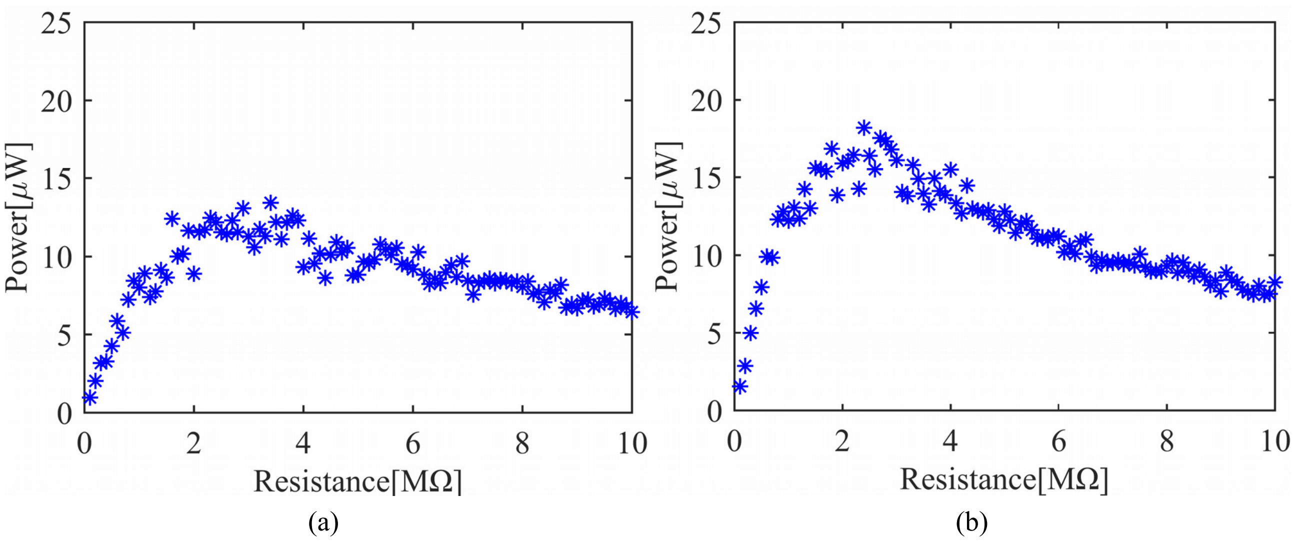


Fig 6. Relationship between output power and resistance under a speed of (a) 4 km/h and (b) 8km/h.

Numerical calculations were applied to maximize the output power and determine the optimum load resistance for tristable energy harvesting from human motion due to the traditional frequency-domain analysis method being inappropriate. Fig 6 illustrates the relationship between average output power of the tristable energy harvester and load resistance under an excitation of 4 km/h and 8 km/h. In the simulations, the load resistance are increasing by 0.1 MΩ every circulation for zero initial conditions. At the excitation of a given speed of motion, the average output power indicates an optimum value within a certain range of load resistance. It is also observed that the output power may undergo a large change (up to 3.93 μW) even when the resistance varies only 0.1 MΩ, which may due to the sensitivity of nonlinear tristable system to the variation of initial parameter and variable human motion excitation. Because of the larger acceleration induced by the larger motion speed, the average output power under excitation of 8 km/h is larger than that of 4 km/h. In addition, the optimum load resistance of the tristable harvester obtained from numerical method is approximately 3.4 MΩ for 4 km/h and 2.4 MΩ for 8 km/h, which indicates a smaller optimum value for a higher speed of motion. The reason for this phenomenon can be viewed from Fig. 5 since the main frequency range of the output voltage shifts to higher frequencies with an increase of motion speed.

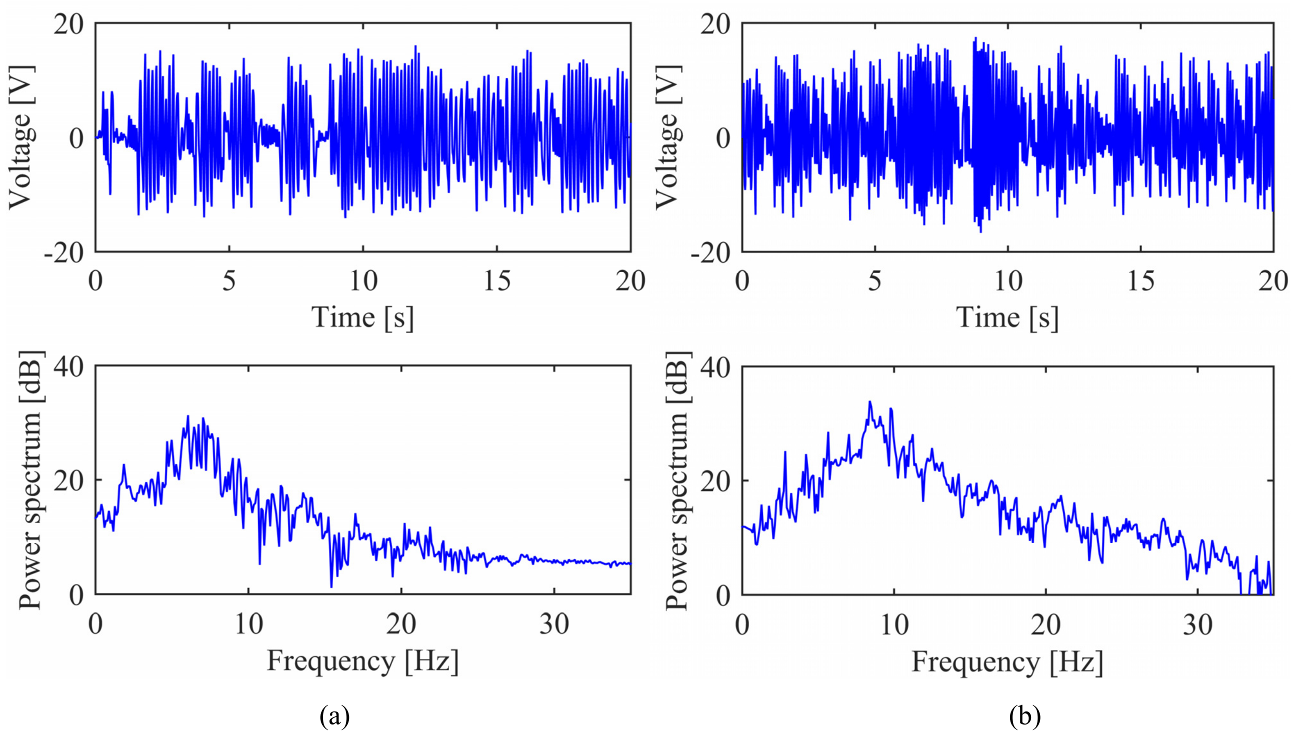
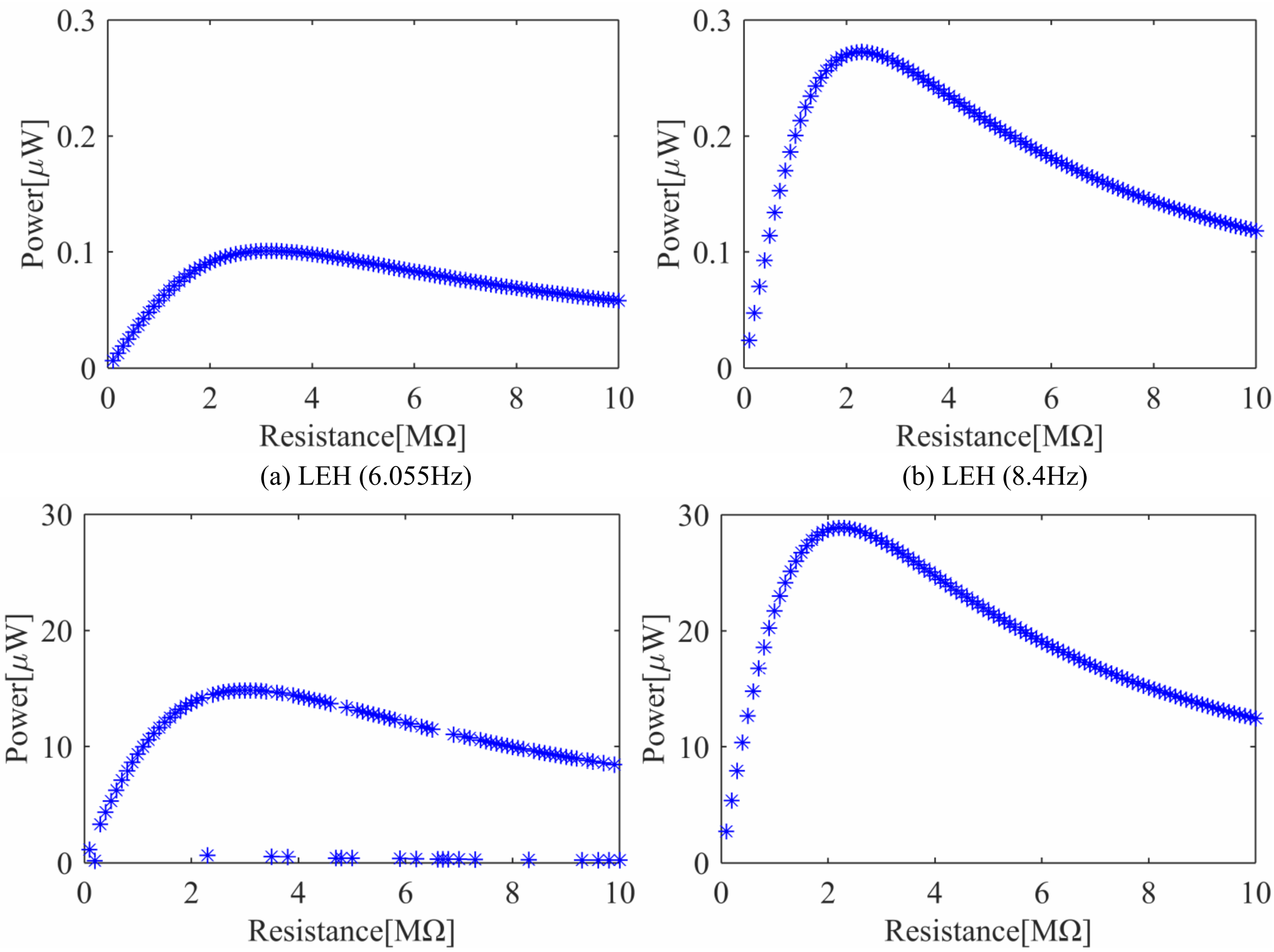


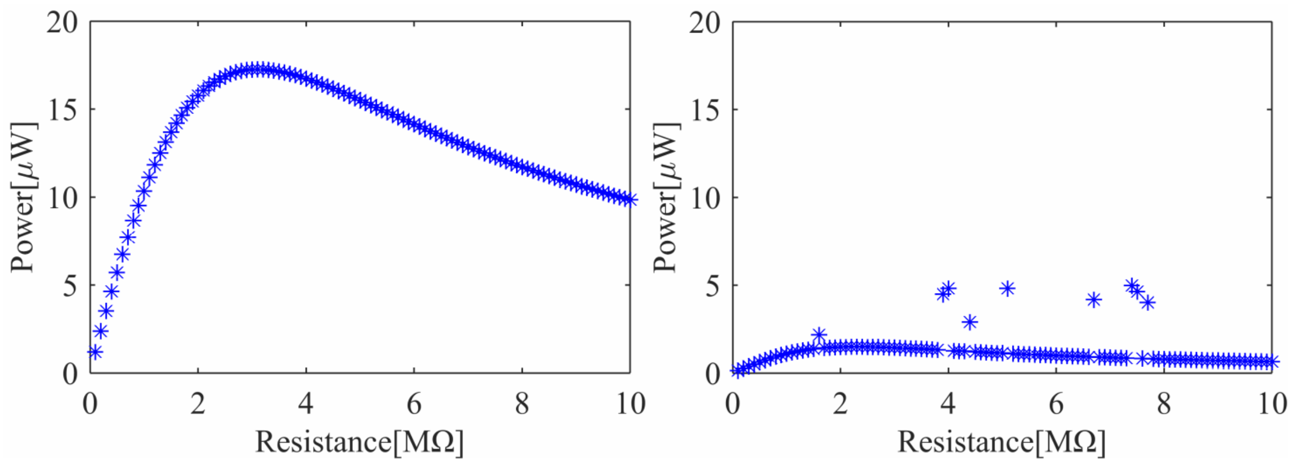
Fig. 7 Voltage response and corresponding power spectrum of the tristable energy harvester excited by the signals of (a) 4 km/h and (b) 8 km/h under each optimum load resistance

Based on the above results, the acceleration and swing angle data under different motion speed were used to excite the tristable harvester under each optimum load resistance, the voltage response and corresponding power spectrum are shown in Fig. 7. It is found that the main frequency of the output voltage is 6.055 Hz for speed of 4 km/h and 8.4 Hz for speed of 8 km/h, which corresponds to the frequency shift behavior shown in Fig. 5. Due to the random and variable characteristics of human motion signals, there is a wide energy distribution in a certain frequency range. Here, we use the main frequency to theoretically calculate (Equation (9)) the optimum load resistance and the resulting value are respectively 3.17 MΩ for speed of 4 km/h and 2.28 MΩ for speed of 8 km/h, which respectively have 6.67% and 5% difference with the simulation results (3.4 MΩ and 2.4 MΩ).



(a) LEH (6.055Hz) (b) LEH (8.4Hz)

(c) BEH (6.055Hz) (d) BEH (8.4Hz)



(e) TEH (6.055Hz)

(f) TEH (8.4Hz)

Fig. 8 Relationships between average output power and the load resistance of the linear (LEH), bistable (BEH) and tristable (TEH) energy harvesters under the two harmonic excitations. (a) LEH, 6.055Hz; (b) LEH, 8.4Hz; (c) BEH, 6.055Hz; (d) BEH, 8.4Hz; (e) TEH, 6.055Hz; (f) TEH, 8.4Hz.

In addition to the simulation of the tristable energy harvesting from real human motion excitation, the corresponding simulations of linear, bistable as well as tristable energy harvesters under harmonic excitation are carried out to compare with the frequency-domain analysis method. Here, two harmonic signals with frequency of 6.055Hz and 8.4Hz and level of 5.5 m/s^2 are simulated to excite the three energy harvesters and relevant information of the three potential energy functions were shown in Fig. 3. During simulation, a stable voltage response is used to calculate the average output power. The relationship between the average output power and load resistance for linear (LEH), bistable (BEH) and tristable (TEH) energy harvesters under two harmonic excitations are shown in Fig. 8. For an excitation frequency of 6.055 Hz, the optimum load resistances of linear, bistable, and tristable energy harvesters have a value of 3.2 MΩ, 3.0 MΩ, and 3.1 MΩ respectively, while for linear and bistable energy harvesters under 8.4 Hz excitation are 2.3 MΩ and 2.2 MΩ, which all are close to the analytical results 3.17 MΩ or 2.28 MΩ calculated from equation (9). Interestingly, there are some scattered points distributed above the main curve for the tristable harvester at a excitation of 8.4 Hz, the reason for this phenomenon is that the cantilever travels across the potential wells for these particular values, while the cantilever undergoes intra-well motion for other values. Similarly, intra-well motion of the cantilever lead to some scattered points below the main curve in Fig. 8 (c). Obviously, a small change in the load resistance leads to the change of dynamic behavior due to the sensitivity of tristable system to initial parameter's variation. Furthermore, it is seen that the given tristable energy harvester performs better at lower frequency excitation, compared to the bistable and linear configurations. In general, there is an optimum load resistance to maximize the average output power and it can be theoretically predicted by equation (9) in the absence of a change in the dynamic behavior of the harvester.

It can be concluded from the above numerical simulations that there is always an optimum load resistance to maximize the output power of the energy harvesters under real human motion excitation as well as the harmonic excitation. Numerical simulation is the best choice to determine the optimum value under human motion excitation, while under harmonic excitation the theoretical method can be applied to calculate the optimum load resistance provided the dynamic behavior of the cantilever does not change.

4. Experimental verification

The experiment setup for verifying the performance of tristable energy harvesting from human motion is shown in Fig. 9 (a), and Fig.9 (b) is the detailed setup of the harvesting device on human leg. An accelerometer CXL04GP3 and an angle sensor BWD-VG100 were used to collect the acceleration and swing angle data of human motion on a treadmill. An oscilloscope MSOX3052A with a probe resistance (R_0) of 10 MΩ was applied to record the experimental data. In the experiment, when a load resistance R_1 is connected into the electric circuit, the actual load resistance R is the parallel value of R_0 and R_1 expressed by R=R_0 R_1/(R_0+ R_1), thus the average output power can be calculated by equation $E(v^2(t))/R$. Further, the subject in the experiment weighted 65kg and was a height of 167cm.

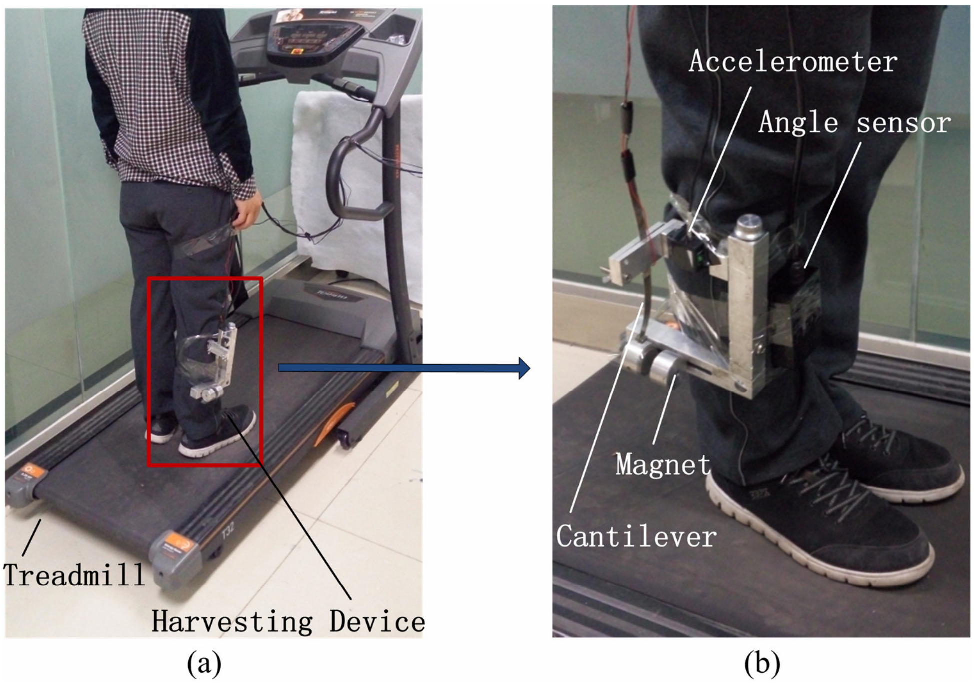
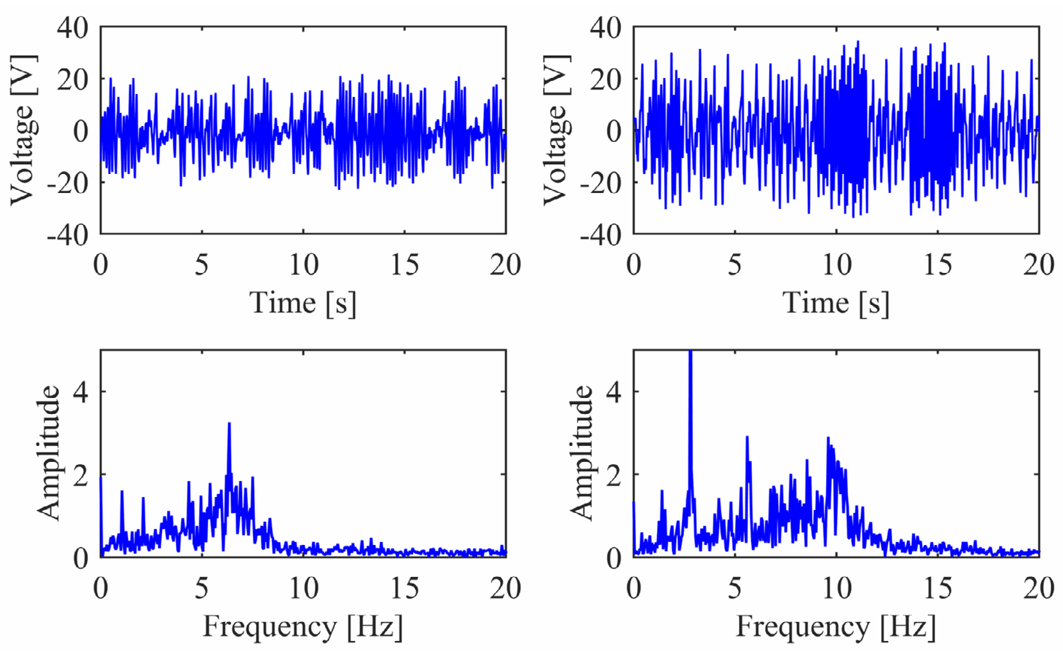


Fig. 9 (a) Experiment setup on a treadmill; (b) enlarged view of harvesting device on human leg



(a) (b)

Fig. 10 Experimental voltage response and frequency spectrum under speed of (a) 4 km/hand (b) 8 km/h

In the condition of an open circuit connection, the experimental voltage response of the tristable energy harvester at speeds of 4 km/h and 8 km/h and the corresponding frequency spectrum are shown in Fig. 10. The tristable oscillator travels across the potential wells to generate a large output voltage (larger than 20V) similar to simulation results shown in Fig.5. The average power output at a speed of 4 km/h is 6.69 μW while the power is 16.31 μW at speed of 8 km/h. It is obvious that the generated average power output is increased with a higher human motion speed. As for the frequency spectrum, there is a local extreme value at the point of human motion step frequency and its double frequency. The dominant frequency shown in Fig. 10 is mainly a result of the nonlinear restoring force and external excitation. It is also observed that the frequency shifting behavior from low to high frequencies are consistent with the simulation.

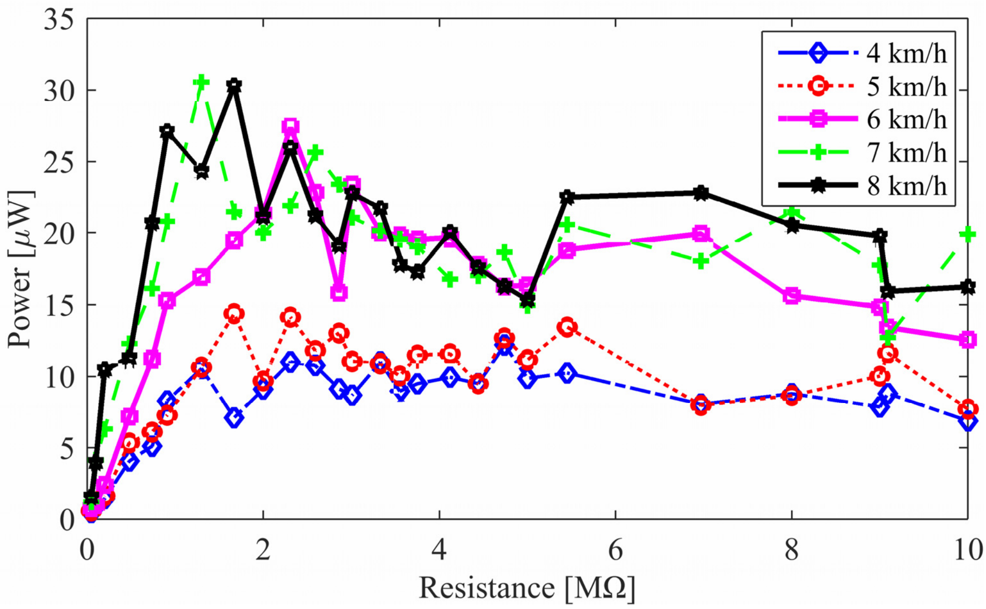


Fig 11. Relationship between output power and resistance at different motion speed for the tristable harvester.

Fig. 11 shows the average output power of tristable energy harvester at various motion speeds and load resistances and the simulation results are shown for speed of 4 km/h and 8 km/h in Fig. 6. Although the random and variable characteristics of low-frequency human motion excitations bring an uncertain influence into the output power, the whole changing trend at different motion speeds are consistent with the simulation results.

It is found from Fig. 11 that the average output power of tristable harvester at lower motion speed of 4 km/h and 5 km/h are much smaller than that of larger motion speed, which distinguish the walking and running motion states since the fact that the subject begins to run at a speed of 6 km/h. Owing to the greater acceleration induced by larger motion speed, the average output power at a given load resistance increases with an increase of speed of motion in most cases. However, considering the randomness of human motion excitation, there also exist an exceptional case in which output power at larger motion speed is smaller than that at lower motion speed. Moreover, the optimum load resistance at the given motion speed 4~8 km/h are respectively 4.74 MΩ, 1.67 MΩ, 2.31 MΩ, 1.3 MΩ and 1.67 MΩ. In addition, the maximum output power generated in the experiments is 30.55 μW at a speed of 7 km/h.

5. Conclusion

This paper numerically and experimentally investigates the optimum load resistance of tristable energy harvesting from real human motion excitation. A theoretical model of tristable energy harvester with time-varying potential energy function is established considering the characteristics of human lower-limb motion and the corresponding experimental system has been built to acquire the data used for numerical investigation. Numerical investigations of tristable energy harvesting from human motion indicate that there always exists an optimum load resistance to maximize the average output power. For comparison, simulations of linear, bistable, and tristable energy harvesters under harmonic excitation show that the frequency domain analysis method can be used to calculate the optimum resistance in the absence of a change in the dynamic behavior of the harvester.

Experimental results under a variety of motion speed treadmill tests and load resistance are in agreement with simulation results to identify the optimum load resistance for tristable energy harvesting from human motion and demonstrate the effectiveness of the proposed numerical method. In addition, the obtained maximum output power of tristable energy harvesting from human motion under optimum load resistance is 30.55 μW, which can be collected to supply electricity for low-power consumption devices such as leadless pacemaker and blood pressure sensor.

Acknowledgments

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